TECHNICAL NOTE

D-1017

AN EXPLORATORY INVESTIGATION OF JET-BLAST EFFECTS ON A DUST-COVERED SURFACE AT LOW AMBIENT PRESSURE

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SUMMARY

A preliminary investigation has been conducted to determine the effects of jet blast, at low ambient pressures, on a surface covered with loose particles. Tests were conducted on configurations having from one to four nozzles at various cant angles and heights above the particle-covered surface.

The results indicate the possibility that problems may exist, due to jet-blast effects, ranging from visibility impairment to damage from impact of the surface particles with the vehicle. In single-nozzle tests the jet blast cleared the dust particles from an annular area on the test surface; however, a buildup of dust particles immediately under the nozzle was observed. This buildup of particles persisted throughout the test run. Multiple-nozzle systems having two or three nozzles in line at cant angles of 0° and placed close together were found to provide sufficient clearing of the landing area without causing surface particles to strike the vehicle.

INTRODUCTION

Interest in jet-blast effects at low ambient pressures arises from the expected need to use high-thrust rockets in close proximity to the surface of the moon or planets having low ambient pressures. Rockets will probably be needed to decelerate a vehicle to allow a safe landing. The high-velocity exhaust gases impinging on the landing surface may present problems ranging from visibility obscurement to vehicle damage. The extent of the problem is dependent on the flow pattern of the high-velocity gases and the surface material.

Similar problems exist at rocket-launching sites and when VTOL aircraft operate in unprepared areas (ref. 1). Considerable effort has been expended in studying these effects; but as far as is known, little work has been put forth in studying these effects at low ambient pressures such as exist on the lunar surface. In order to obtain an

understanding of these effects, the present investigation was conducted using small-scale supersonic jets operating in an evacuated bell jar. All the tests discussed herein were conducted with balsa-dust particles in the bell jar so that the flow patterns could be observed without regard to types or size of lunar material they might represent. High-speed motion pictures were taken in order to record the test results.

APPARATUS AND PROCEDURE

The apparatus used in the investigation is shown in figure 1. The bell jar in which the test nozzles were mounted was 18 inches in diameter and 30 inches in height. The bell jar was mounted on a 1-inch-thick steel base plate which served as the simulated landing surface. This bell jar and base plate were sealed with vacuum putty. The vacuum chamber was evacuated by a fore pump and two diffusion pumps in parallel. The inlet pipe to the nozzles in the vacuum chamber was sealed off from the atmosphere by a thin Mylar diaphragm that could be punctured to introduce atmospheric pressure to the nozzle block.

Two different nozzle designs, based on table II of reference 2, were used during the tests. Nozzle A was designed for flow at a Mach number of 3 and was used only in a single-nozzle configuration. Nozzle A was therefore constructed as an integral part of its nozzle block (fig. 2). Nozzle B was designed for flow at a Mach number of 3.4 and for use in multiple-nozzle configurations. Four nozzle blocks were constructed to hold from one to five nozzles of design B. Each nozzle block had the center nozzle slot at 0° cant angle and four additional nozzle slots in an evenly spaced array surrounding the center. The cant angle is defined as the angle between the vertical and the center line of the nozzle. The outer four slots were at a different cant angle for each nozzle block, the cant angles being 0°, 10°, 20°, or 30°. The detail dimensions of nozzle B and one of the nozzle blocks is given in figure 2.

A thermocouple gage was used to measure the ambient starting pressure in the bell jar. This gage was capable of measuring pressures from 5 to 1,000 microns of mercury (9.65×10^{-6} lb/sq in. to 1.93×10^{-2} lb/sq in., respectively).

The tests were conducted with an initial ambient pressure in the vacuum chamber of approximately 9.65×10^{-6} pounds per square inch. After the high-speed camera had been brought up to speed (approximately 5,500 frames per second), supersonic flow was initiated by puncturing a diaphragm which vented the nozzle block to atmospheric pressure.

In preliminary tests the base plate of the bell jar was completely covered with particles, but it was found that the cloud of particles produced was too dense to permit observation and filming. Therefore, in order to film the data presented herein, small mounds of particles were uniformly distributed over the test area. Preliminary tests conducted with 0.075-inch glass beads, rice grains, and balsa dust produced similar results. The flow patterns obtained with the balsa dust, however, were the most easily observed and tended to be more quickly developed than those obtained with heavier particles. Therefore, the data presented herein were obtained by using balsa-dust particles. In addition to the particles arrayed on the base plate, twelve 1-inch-diameter trays of balsa dust were stacked 1/2 inch apart in a column 1 inch from the inner wall of the bell jar to determine whether the flow conditions would cause any particle dispersion at these locations. Also, tufts were strung across the center of the test chamber at the elevation of the nozzle exit plane to help visualize flow during some of the early tests. Neither the tufts nor the balsa dust on the trays reacted substantially to the low-density flow, and consequently use of these devices was discontinued in subsequent tests.

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Tests were conducted with nozzle configurations having from one to four nozzles and with nozzle cant angles of 0°, 10°, 20°, and 30°. These configurations were tested with the exit plane of the nozzles positioned 2, 4, or 6 inches above the base plate, which for nozzle A was 8, 16, or 24 throat diameters above the base plate and for nozzle B was 40, 80, or 120 throat diameters.

The effective test time was considered to extend from the start of the high-velocity flow until the particles began to strike the walls of the bell jar. The time was dependent on the nozzle size and configuration used; but for most of the tests conducted, the test time was less than 0.1 second. In some of the tests (particularly the ones in which multiple nozzles and large cant angles were used) once the particle pattern had developed this pattern persisted even after particles began to strike the walls of the bell jar. The average ambient-pressure rise in the bell jar for a test time of approximately 0.1 second was computed for a single nozzle of design B, and the pressure ratio between the nozzle chamber pressure and the ambient pressure in the test chamber decreased from 200,000 to 5,000.

RESULTS AND DISCUSSION

A total of 80 tests were conducted during the investigation. The particle flow patterns which developed during the various tests were obtained from the high-speed motion-picture records. These motion-picture records are available on loan. A request card form and a

description of the film will be found at the back of this paper, on the page immediately preceding the abstract page. Since the flow processes could not be adequately shown by reproductions of the motion-picture frames, drawings made from observations of the motion pictures have been used to illustrate these processes. The results of the tests are given in accordance with the number of nozzles used.

Single-Nozzle Tests

In all single-nozzle tests, a solid layer of balsa dust was spread L
out over the base plate. At the start of the jet blast a part of the 1
base plate was rapidly cleared of particles. The cleared portion was 1
not directly under the nozzle, but consisted of an annular area around 9
the point where the projected center line of the nozzle would intersect 0
the base plate. As the test continued, the outside diameter of the cleared annulus increased, but the inside diameter of the annulus remained relatively constant; however, the height of the mound in the small center circle increased until it reached a height of approximately half the distance between the nozzle exit and the base plate. Once the center mound of particles had been developed it persisted until well after the test had terminated. There is some evidence from the pressure-distribution studies presented in reference 3 that the central mound may be a function of nozzle design, or a transient effect, or both. Two effects were noted as a result of changing the height of the nozzle exit above the base plate: (1) The inside diameter of the annulus or central mound decreased as nozzle height increased. (2) The height of the central mound increased as the nozzle height increased. An example of the pattern observed is shown in figure 3.

In the single-nozzle tests, as well as in the other tests conducted, the effects of the dispersion of particles on a pilot's visibility and the ground erosion due to deep dust could not be determined.

Multiple-Nozzle Tests

Effect of increase in bell-jar pressure.- The results of the multiple-nozzle tests could have been influenced to a greater extent by the increase in bell-jar pressure during the run than those of the single-nozzle tests. However, it is believed that regardless of the pressure the greater part of the momentum of a jet is confined to a central core surrounding the jet axis. The effect of the change in pressure on the size of this central core was believed to be negligible, even though the pressure change would cause the angle between the jet boundary and the jet axis (based on the Prandtl-Meyer angle from ref. 4) for one nozzle of design B to decrease from approximately 70° to approximately 48° in approximately 0.1 second of test time. Analysis of the motion-picture

records further substantiated this belief, as throughout the test runs the jets appeared to be separated except for the tests of the configuration with two nozzles at 0° cant angle. In light of these observations it was concluded that the increase in bell-jar pressure during a test had no appreciable effect on the particle movement due to the jet blast. Additional research in this area is necessary in order to determine the exact effect of the pressure increase.

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<u>Two-nozzle configurations</u>.- In order to ascertain the effect of varying the cant angle, tests were conducted on two-nozzle configurations at cant angles of 0°, 10°, 20°, and 30°. At the start of the jet blast from two nozzles at 0° cant angle, the balsa-dust particles moved outward from under the nozzles, primarily in a direction parallel to a plane through the center lines of the nozzles, until the entire area under the nozzles was swept clear of particles. A sequence of frames taken from the high-speed motion-picture record of this test with the nozzles located 4 inches above the base plate is presented as figure 4. Varying the height above the base plate for this nozzle configuration had no appreciable effect.

The results for the series of runs with the nozzles at 0° cant angle indicate that the two jets expanded into each other before reaching the base plate, so that they acted essentially the same as a single jet.

The particle movement which took place during the tests of the two-nozzle configurations having both nozzles canted at 10°, 20°, or 30° was observed to follow a basic pattern. At the start of the high-velocity flow, an outward movement of particles was observed, as in the test at 0° cant angle, but particles were also observed moving inward in such a manner that a ridge of particles accumulated in an area extending across the base plate perpendicular to a plane passing through the center lines of the nozzles. The width and height of this ridge of particles was observed to be a function of cant angle as well as height of the nozzle exit above the base plate. As cant angle was increased from 0° to 30°, both the width and height of the ridge increased. At a given cant angle, as nozzle height was increased both the width and height of the ridge decreased. In all the tests in which the ridge was observed, an upward flow of particles from the ridge to the area of the nozzle block was noted. The number of particles which were observed impacting the nozzle block increased as cant angle increased and height of the nozzle exits above the base plate decreased. Figure 5 is an illustration of the effect noted during a test with two nozzles each canted at 30°. This pattern persisted after it had once formed except for the test at 10° cant angle. In this test the basic pattern developed, but soon became unstable and was dispersed leaving the base plate clear of particles at the end of the test.

<u>Three-nozzle configurations</u>.- The three-nozzle tests were conducted with the three nozzles in line; the center nozzle was kept at 0° cant angle while the outer two nozzles were each canted away from the center nozzle at either 10°, 20°, or 30°. During each of the tests a basic pattern of particle buildup was observed. At the center line the high-velocity-flow particle movement started radially outward from the areas on the base plate directly under each nozzle center line. These areas were quickly cleared of particles but between each of the cleared areas a ridge of particles accumulated which extended across the base plate. The width and height of these two ridges and the time that the ridges persisted were determined by the cant angle and the height of the nozzle exits above the base plate. Although the two ridges developed in all the tests with the nozzles canted at 10°, these ridges were unstable and were quickly dispersed. After the ridge breakup, the base plate was left cleared of particles. For the tests where the nozzles were canted at 20° or 30°, the ridges developed and persisted throughout the test. The width and height of the ridges were observed to decrease as the distance between the nozzle exits and the base plate was increased. In all the tests, particles were observed being carried upward from the ridges to the area of the nozzle block between the nozzles.

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The number of particles striking the nozzle decreased with decreasing cant angle, and for a given cant angle the number of these impacting particles decreased as nozzle height increased. Figure 6 is an illustration showing the results of a three-nozzle test with the outer nozzles each canted at 30°.

<u>Four-nozzle configurations</u>.- In the four-nozzle tests the nozzles were evenly spaced around the perimeter of a circle, and no center nozzle was used. The nozzles, when canted, were canted outward from the center of the circle. A basic particle flow pattern could be observed in all the four-nozzle tests. At the inception of the high-velocity flow, an area under each nozzle began to clear of particles. As time progressed, two distinct ridges of particles extending across the base plate became apparent. The ridges formed were perpendicular to each other and intersected at the center of the base plate directly under the center of the nozzle block. At the area of intersection a column of particles formed which extended from the base plate up to the nozzle block. An illustration of the flow pattern observed for a four-nozzle configuration having the nozzles canted at 30° is presented in figure 7.

Variation in cant angle during the four-nozzle tests affected the width and depth of the ridges formed as well as the diameter of the column that was created at the intersection of the ridges. In the test of four nozzles having 0° cant angles, the ridges existed only for a short period and the column seemed to culminate at a height of about half the distance of the nozzle exits from the base plate. In the other

tests the ridges persisted, and as cant angle increased their width and depth increased. Also, the diameter and height of the column observed increased as cant angle increased.

In all the four-nozzle configurations tested it was noted that as the height of the nozzle exits above the base plate was increased, the height and width of the ridges as well as the diameter of the column observed decreased. In all but the test for 0° cant angle, the column extended from the base plate upward to the area of the nozzle block between the nozzles.

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CONCLUDING REMARKS

An investigation of the movement of balsa dust under the influence of single and multiple supersonic jets has been conducted in an evacuated bell jar. Results of single-nozzle jet-blast tests indicated the possibility of a buildup of a pile of particles under the center of the nozzle. Further research is necessary to determine whether this buildup is general, a starting transient effect, or a function of nozzle design. A multiple-nozzle system having two or three nozzles in line at cant angles of 0° and placed close together cleared the base plate without causing surface particles to strike the nozzle block.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., November 9, 1961.

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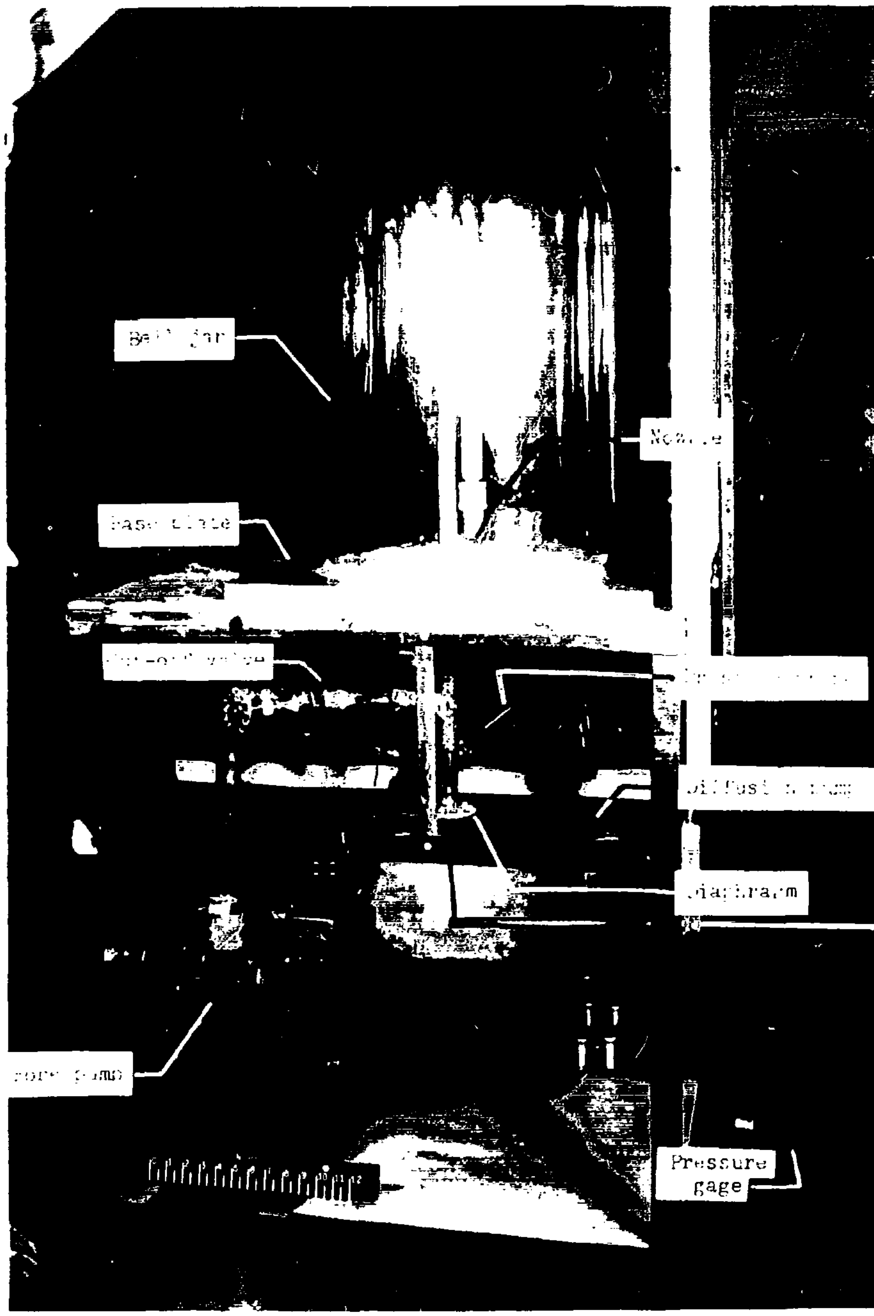

Figure [illegible].- Photograph of test apparatus. L-60-1505.1

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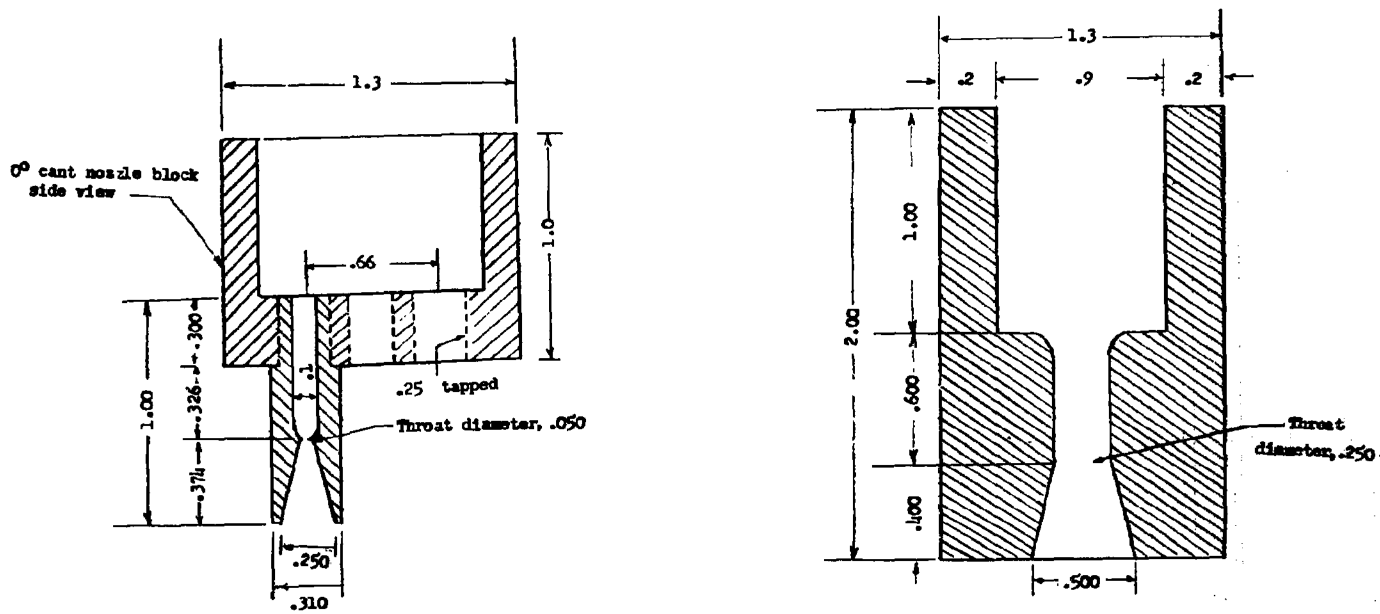

Nozzle B, exit velocity approximately 1900 ft/sec

Nozzle A, exit velocity approximately 1700 ft/sec

Figure 2.- Drawing of nozzles (all dimensions given in inches).

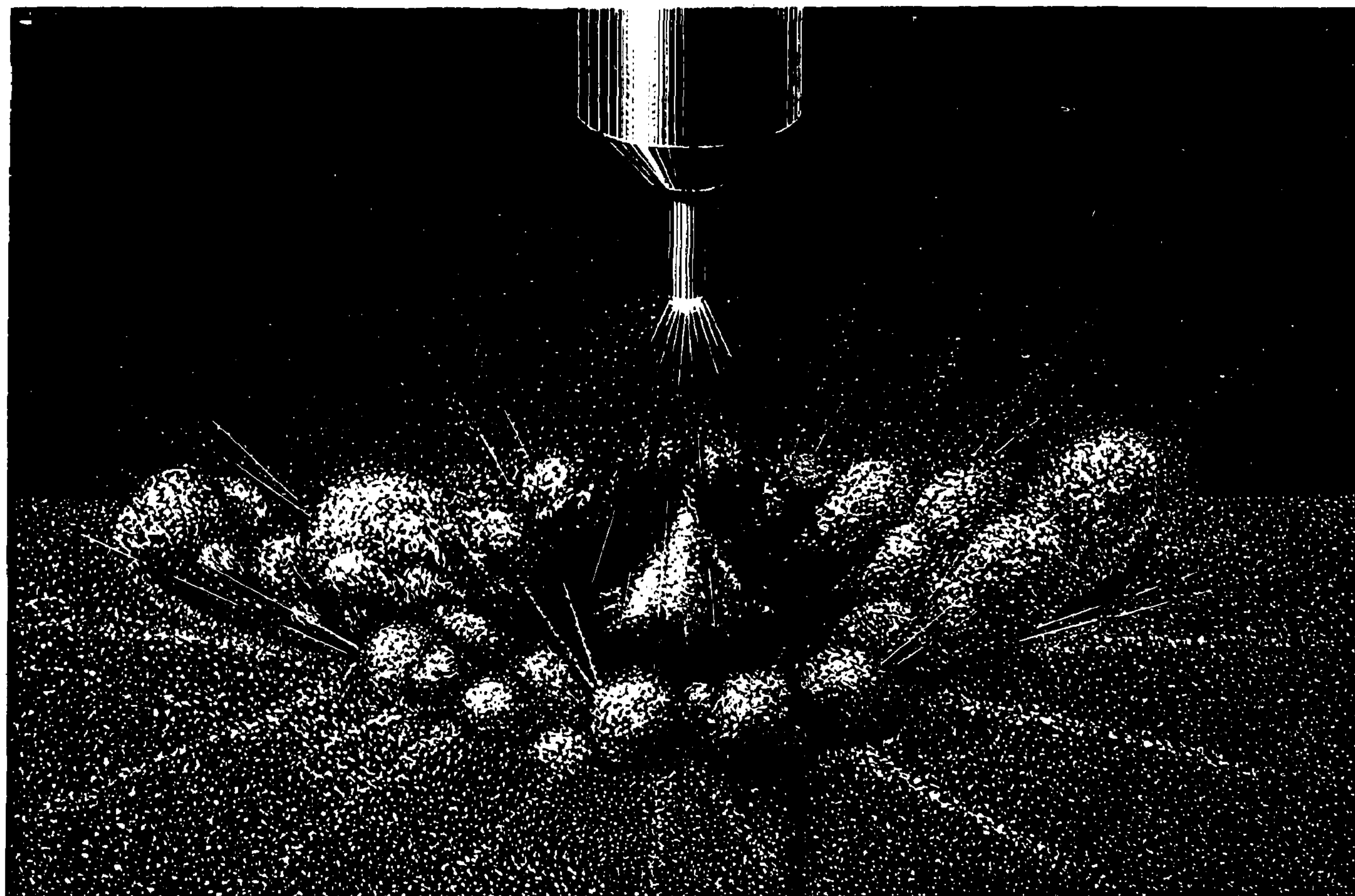

Figure 3.- Example of flow pattern observed in single-nozzle tests.

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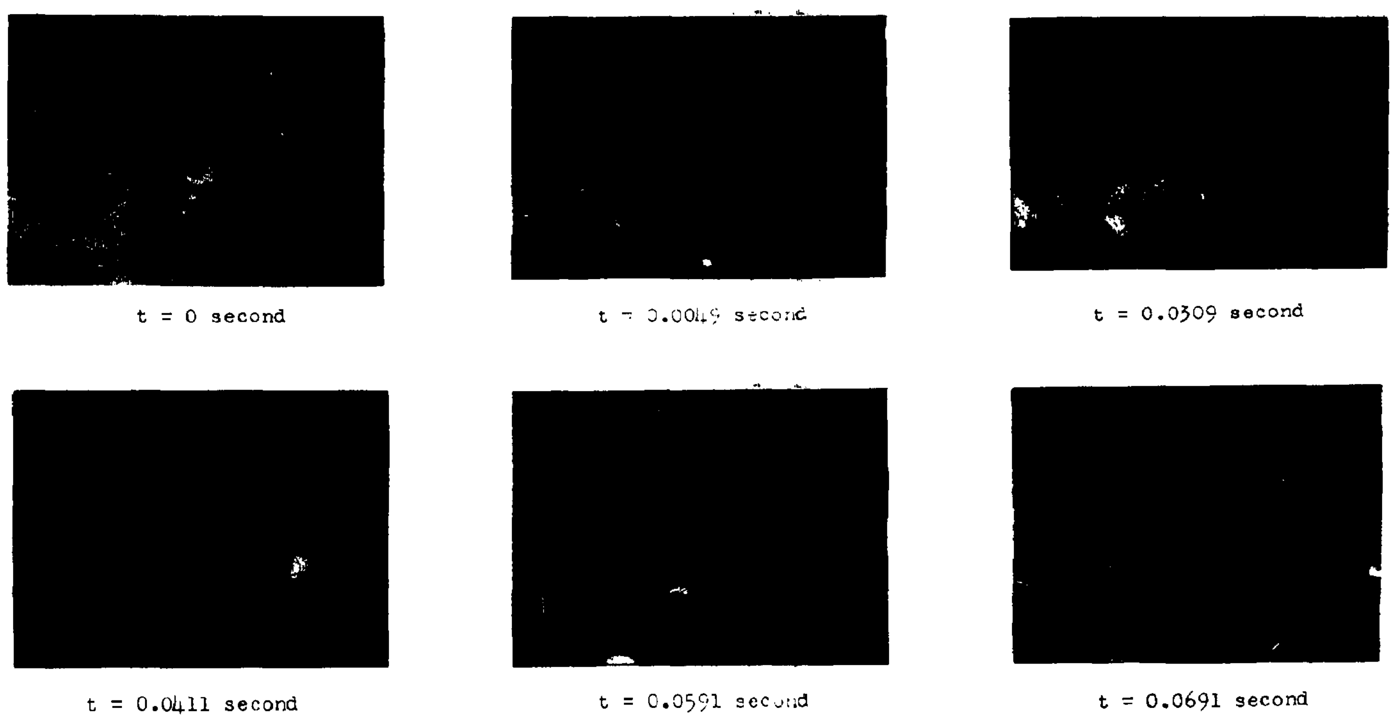

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Figure 4.- Flow pattern observed for two-nozzle configuration with cant angle of 0°, located 4 inches above base plate. The symbol t is the time from the initiation of the high-velocity flow.

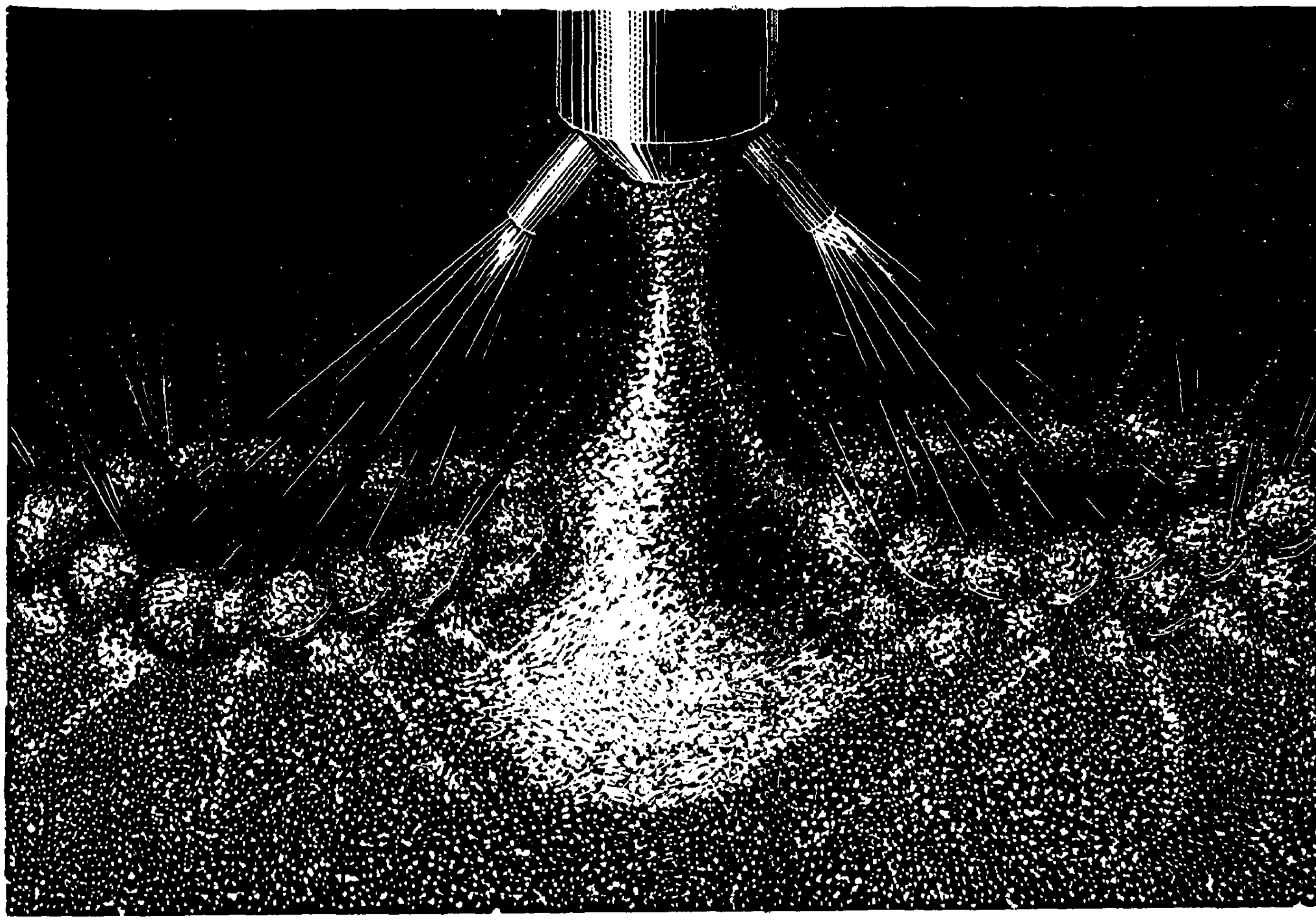

Figure 5.- Example of flow pattern observed with two nozzles, each canted 30°.

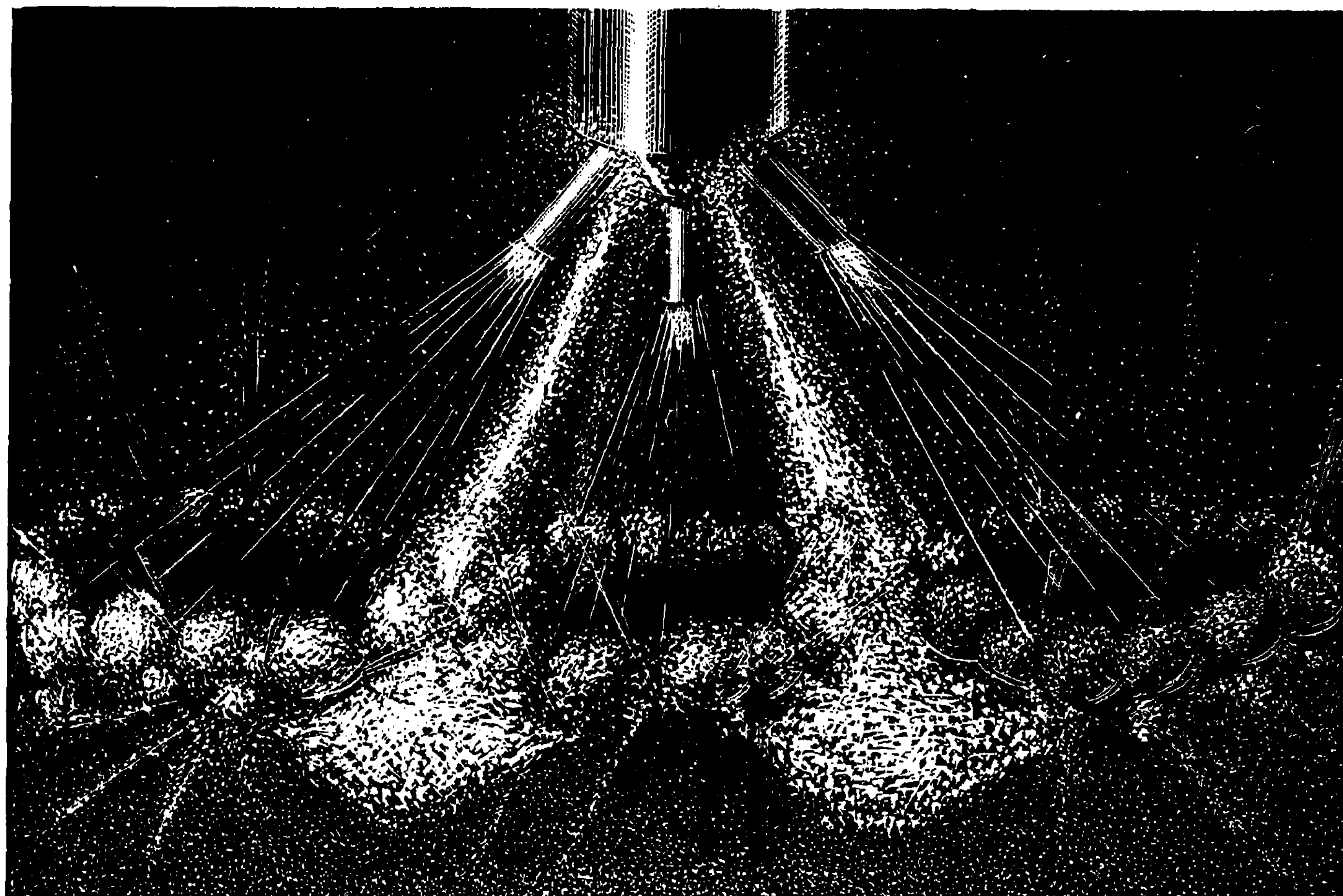

Figure 6.- Example of flow pattern observed with three nozzles, the outer two nozzles each canted 30°.

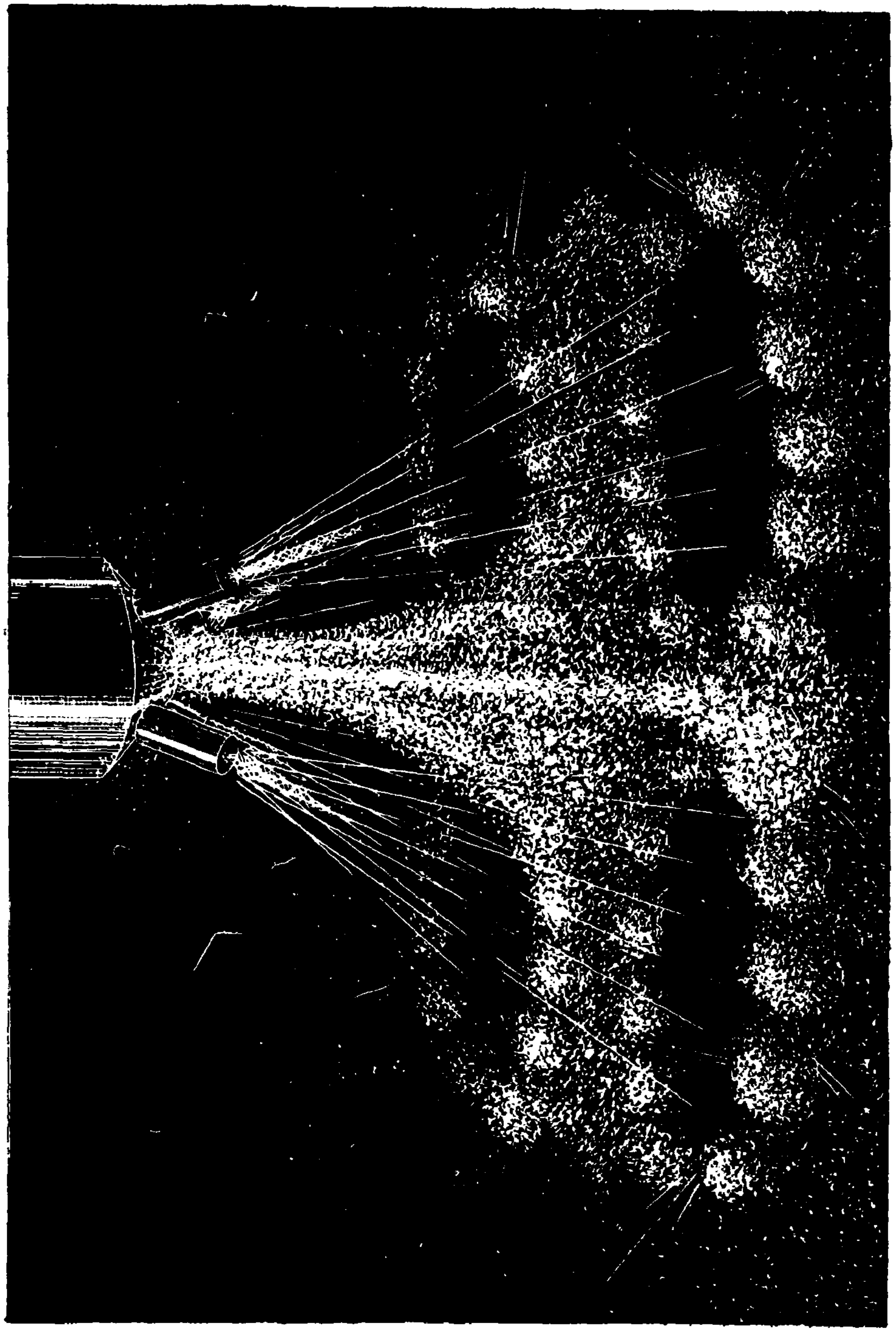

Figure 7.- Example of flow pattern observed with four nozzles located 4 inches from base plate, each nozzle canted 30°.

A motion-picture film supplement is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm, 20 min, B&W, silent) gives a sample run of each configuration tested and shows the effect of varying the number of nozzles, nozzle height, and cant angle.

Requests for the film should be addressed to the

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A preliminary investigation was conducted to determine the effects of jet blast, at low ambient pressures, on a surface covered with loose particles. The results indicate that the design and operation of any vehicle using braking rockets in close proximity to a particle-covered surface must take into consideration the effects of the jet blast on the landing area and on the vehicle itself.

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